Unlocking the Mystery of Columbia's Tragic Accident Through Materials Characterization

Presented to

Mississippi State University Materials Working Group

By

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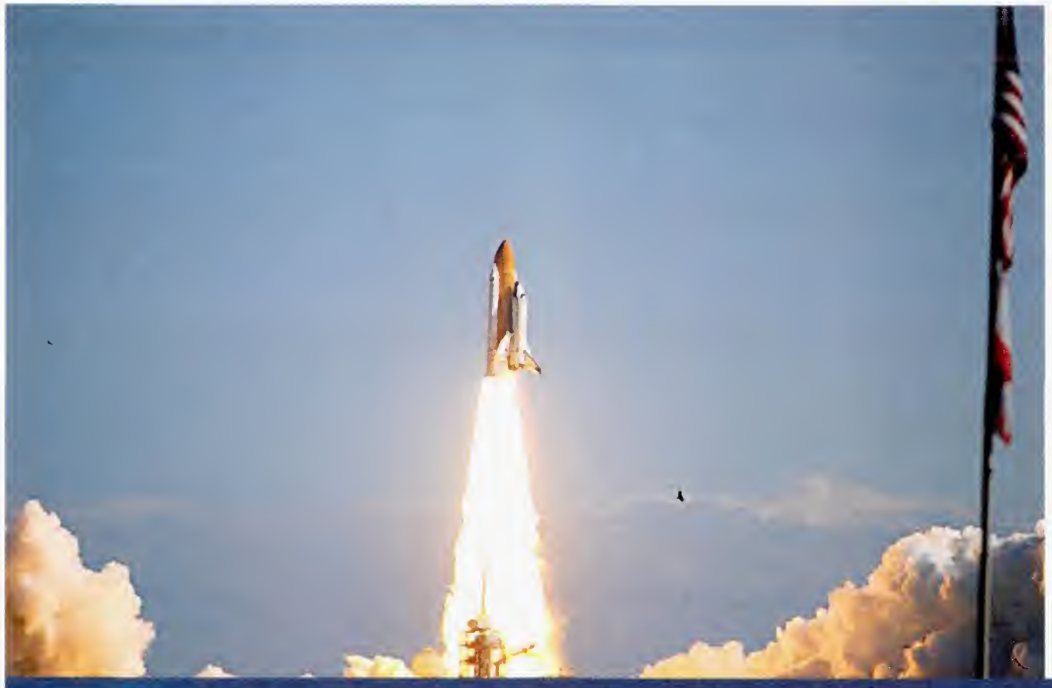
October 15th, 2003

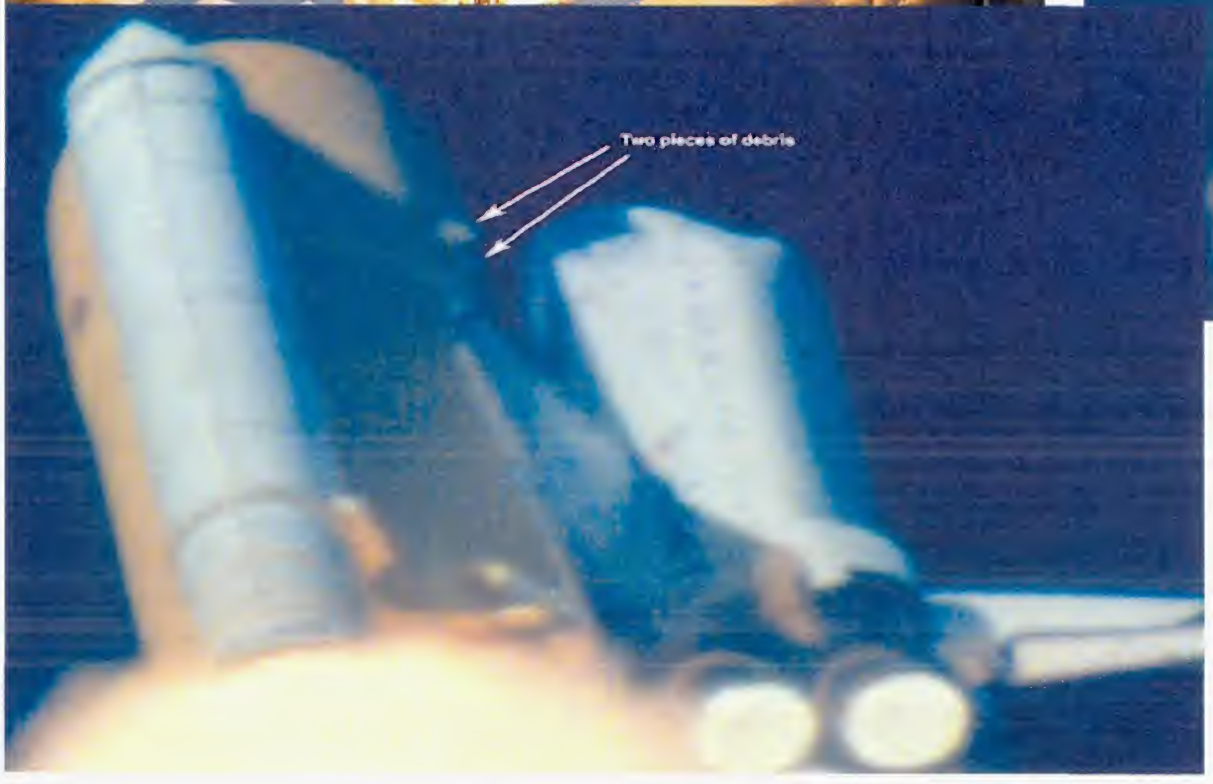
Acknowledgement: This work is a result of a team effort involving KSC, JSC, MSFC, LaRC, GRC, Boeing, USA and Columbia Accident Investigation Board personnel.

IN MEMORY
OF STS-107
ASTRONAUTS

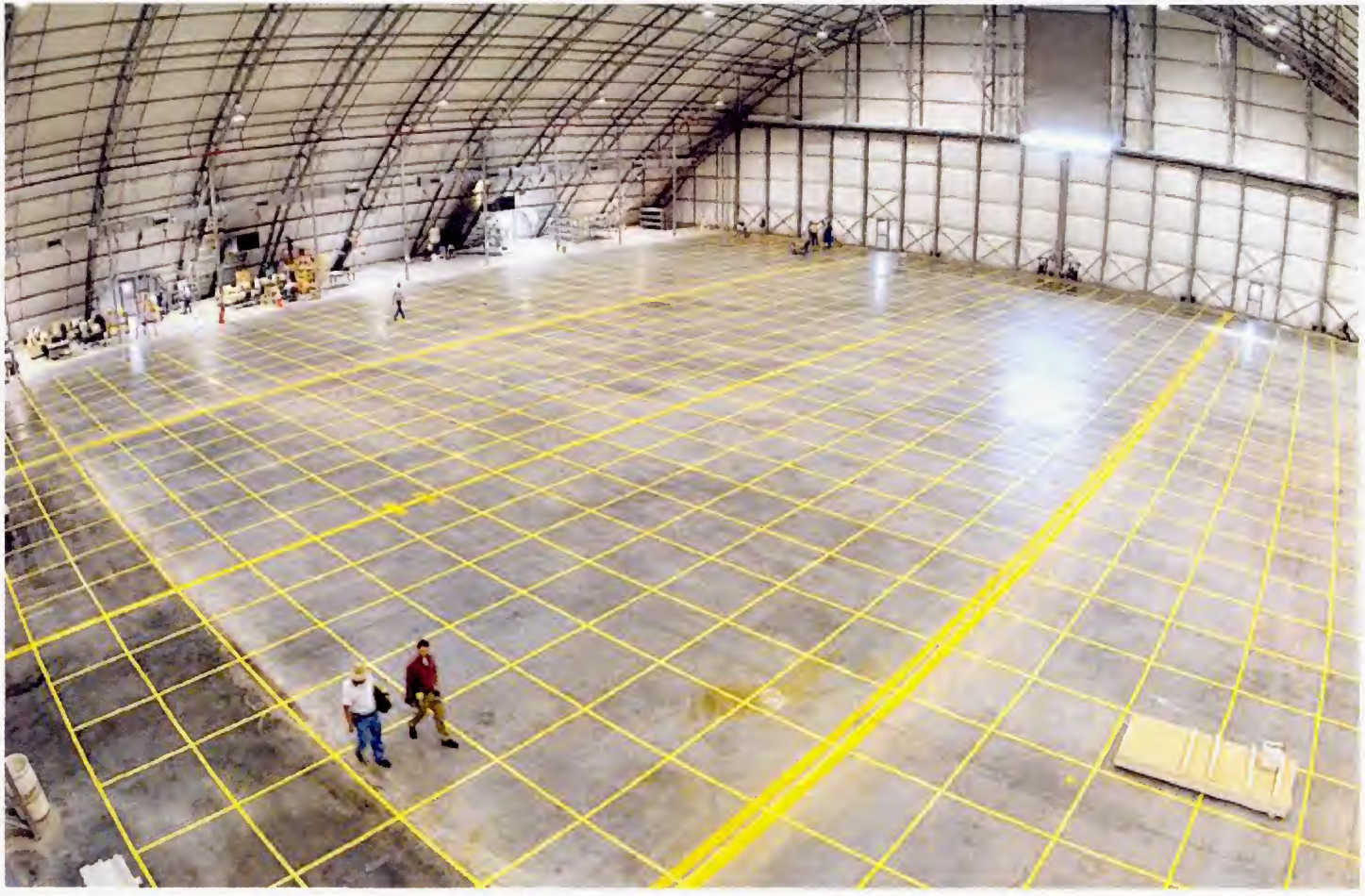
Space Shuttle Columbia In Orbiter Processing Facility (OPF) and Rollout to Vehicle Assembly Building (VAB).

STS 107 Rollout and on Launch Pad





STS107 Launch



Shuttle Landing Facility Hangar Prior to Debris Recovery

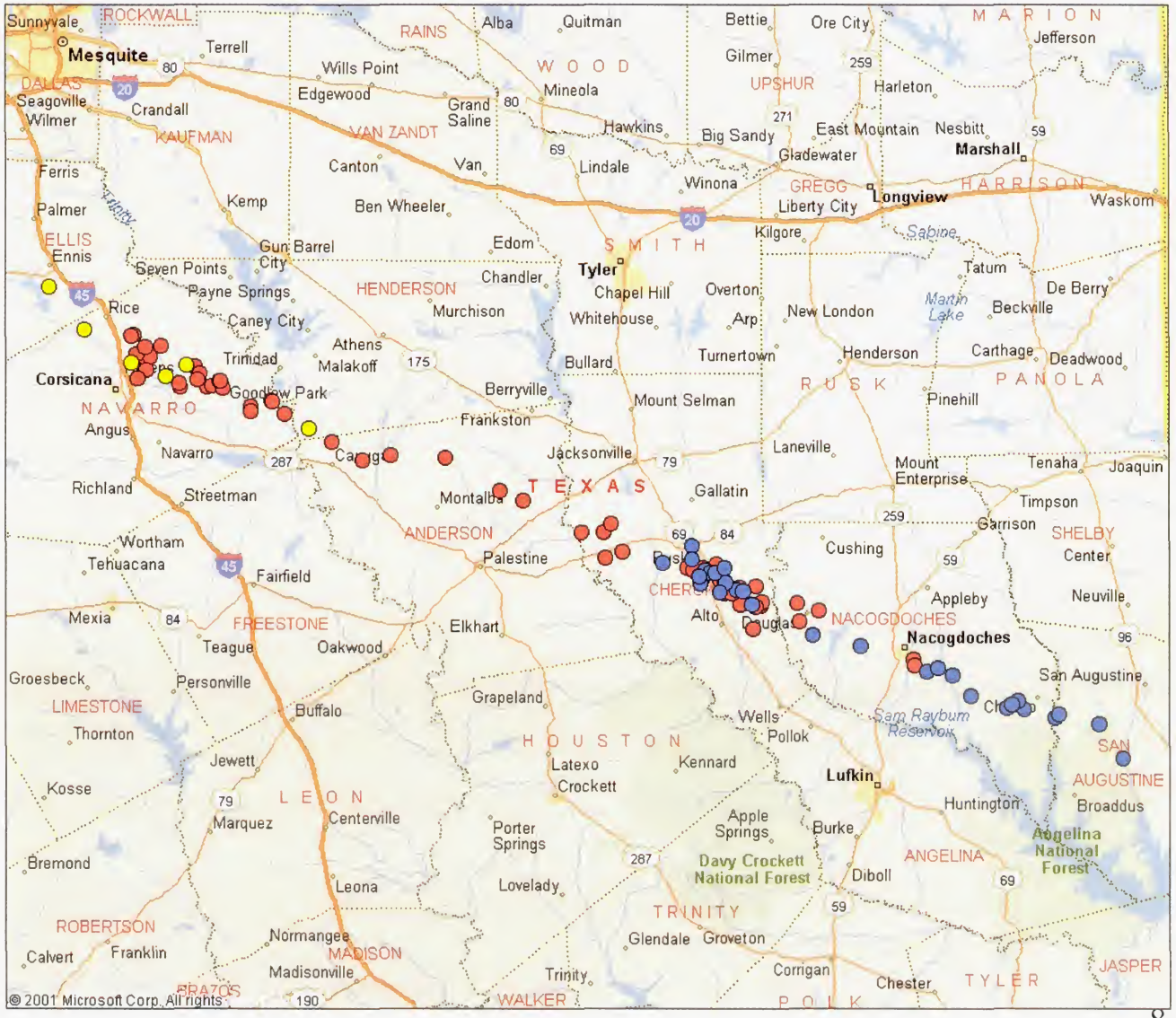
STS107 Reconstruction - Wing and Underbelly Surfaces Only

Location of each part found tracked on map - Trend emerges.

Left Wing RCC

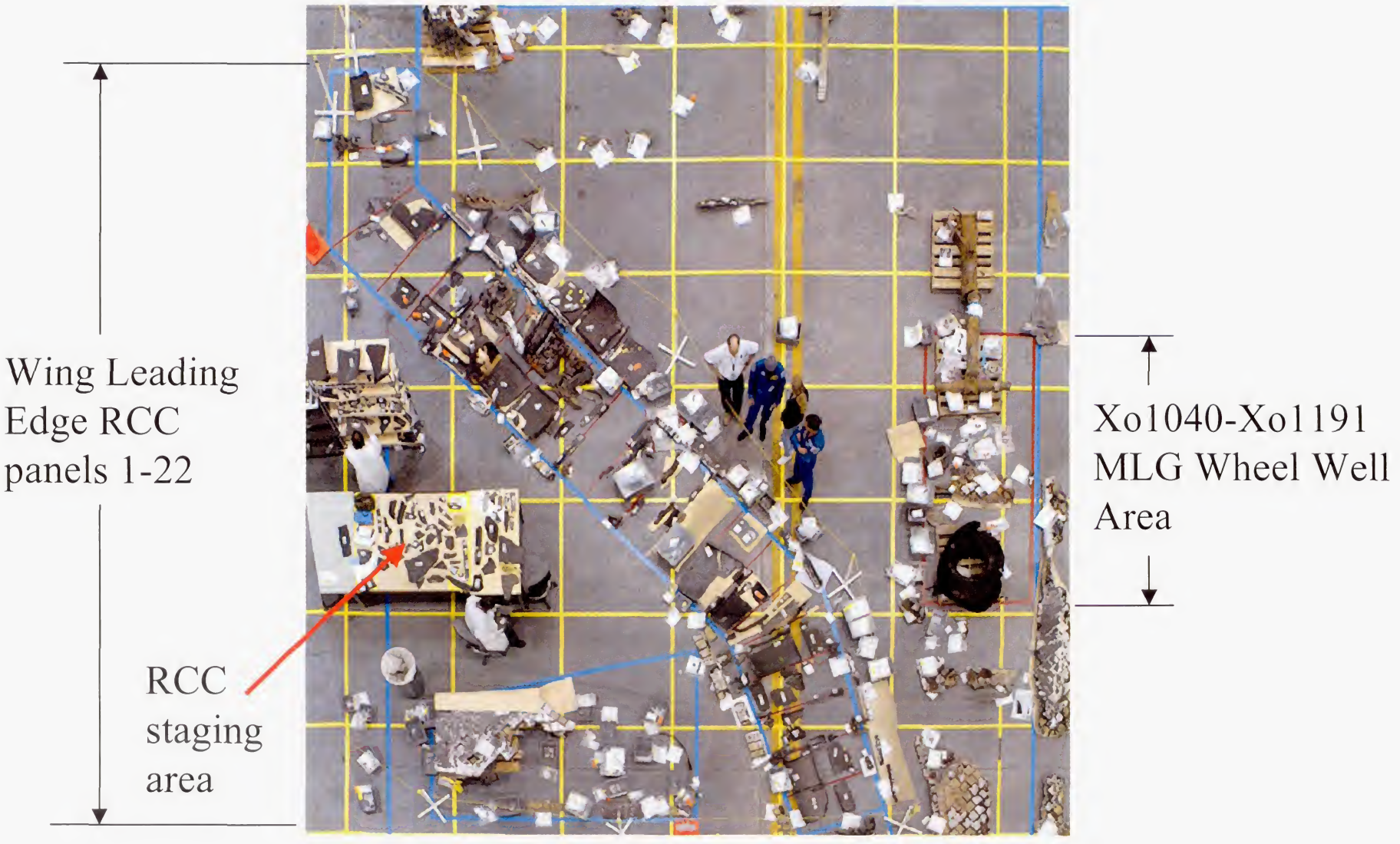
Left Wing Eroded RCC

Right Wing RCC



Believed to be Left Wing Main Landing Gear Assembly

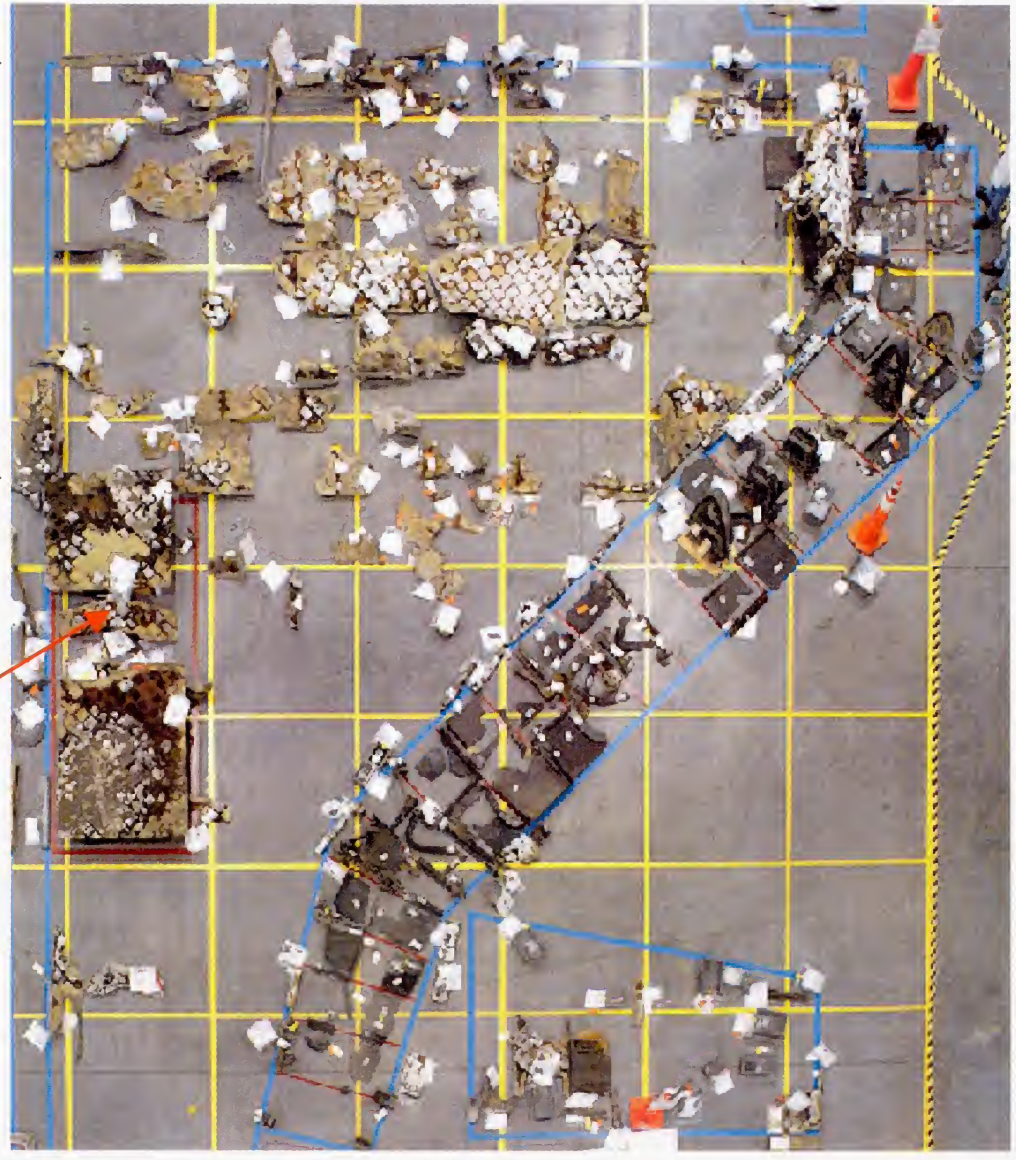
Part Adjacent to Left Main Landing Gear Door



Left Wing Leading Edge Recovered Parts – Panels 1-22

Torque Box
Xo1191-Xo1365

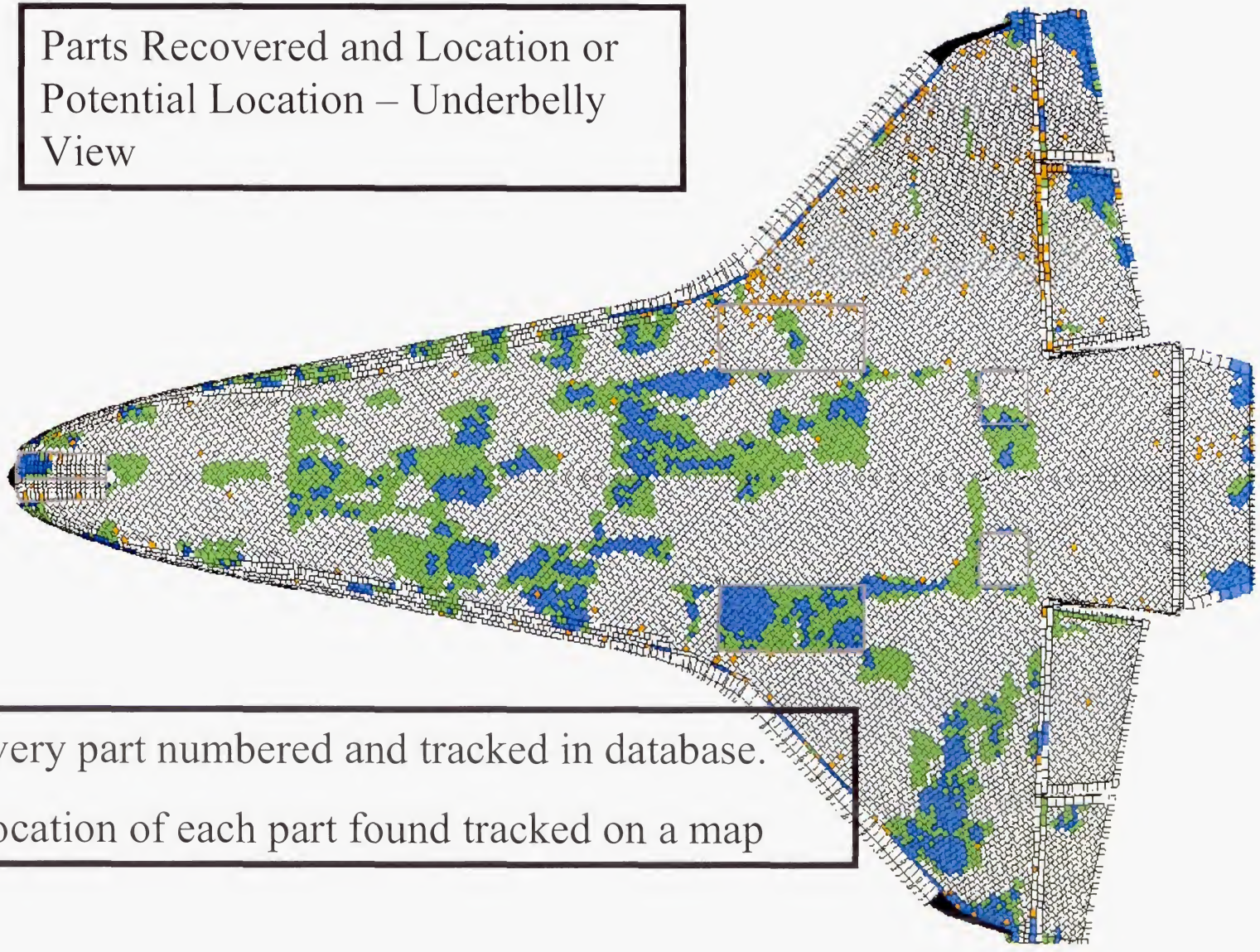
RH
MLG
Door



Intermediate Wing
Xo1040-Xo1191

Right Wing Leading Edge Recovered Parts – Panels 1-22

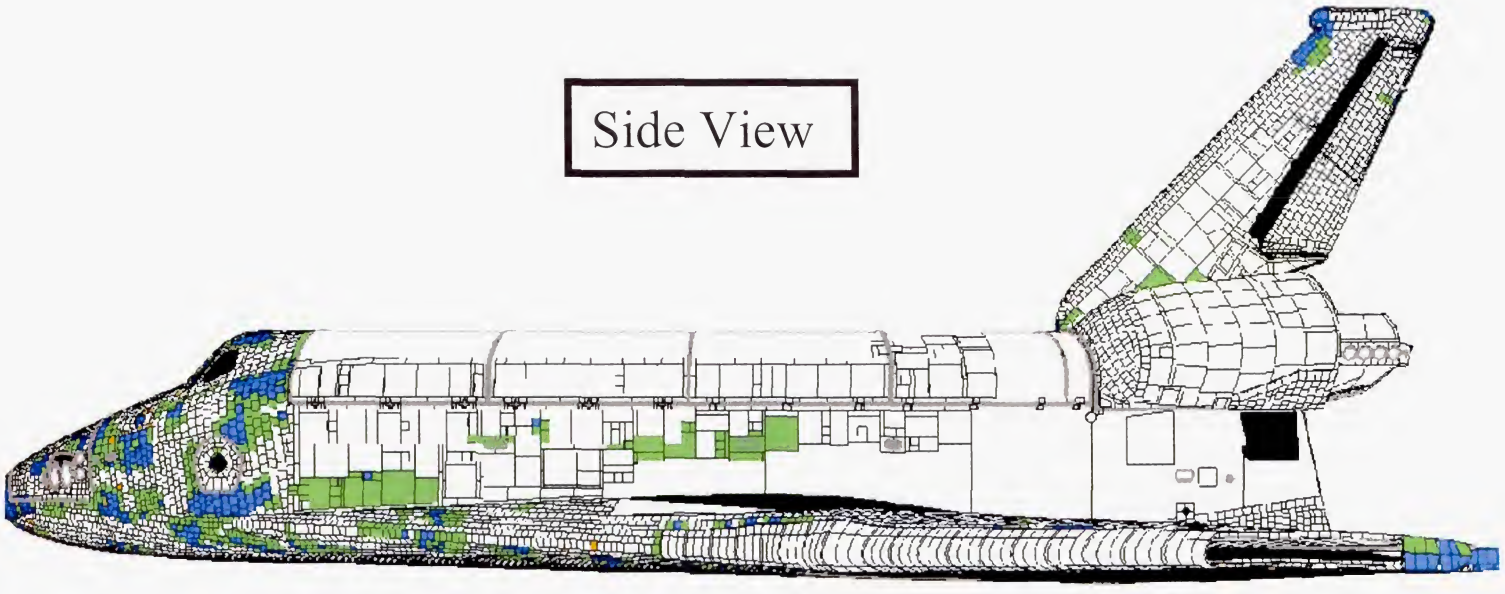
Parts Recovered and Location or Potential Location – Underbelly View



Every part numbered and tracked in database.

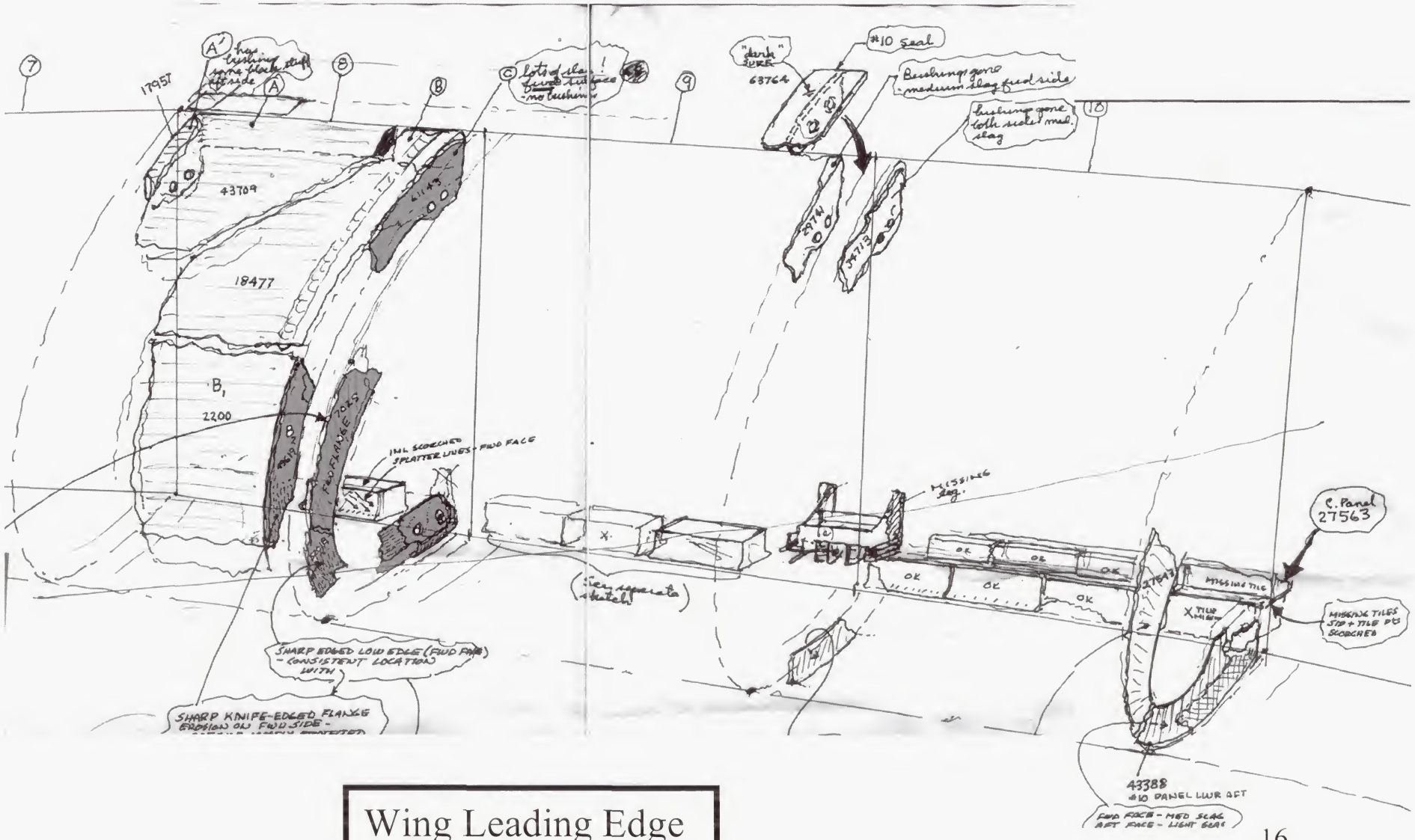
Location of each part found tracked on a map

Side View



Booing EMapo/R http://xb70.kcc.nasa.gov/[illegible]

Hardware Forensic Team Member Reconstruction Schematic & Notes



Wing Leading Edge

Left Wing Leading Edge
Final 3D Reconstruction

Left Wing Tile
Reconstruction

Leading Edge Tiles

STS107 Reconstruction Team

M&P Organizational Structure

- Hardware Forensics Team – "Gray Beard" members from Boeing, NASA Langley, NASA Johnson.
  - Evaluate Debris
  - Interact, disseminate and apply findings with other working groups (reconstruction, scenario, fault tree, etc.)
  - Direct specific Failure Analysis. Participate in determining Cause of Failure.
- Materials & Processes Problem Resolution Team.
  - Establish procedures – sample extraction, cleaning…
  - Interface with Hardware Forensics Team.
  - Generate Failure Analysis Plans.
  - Execute Failure Analysis Plans. Provide "Concrete Data"
  - Members included Boeing, USA, NASA KSC, NASA JSC, NASA MSFC, NASA GRC

When and Where to Begin Failure Analysis?

- Complex and Challenging Analysis.
- New material added weekly.
- Parts originally located could move as more parts are received.
- Where to Begin? What Questions to ask?
- How many parts to analyze?
- Who to and how to prioritize Failure Analysis?
- How to distinguish between damage in flight vs free fall and impact.
- Initial Constraint – Perform all analysis locally at KSC. Parts could not be sent outside even to other NASA centers.
- CAIB owned the hardware. NASA only in support role.
- Every step/analysis/procedure required documentation through approval from CAIB and NAIT.

When and Where to Begin Failure Analysis?

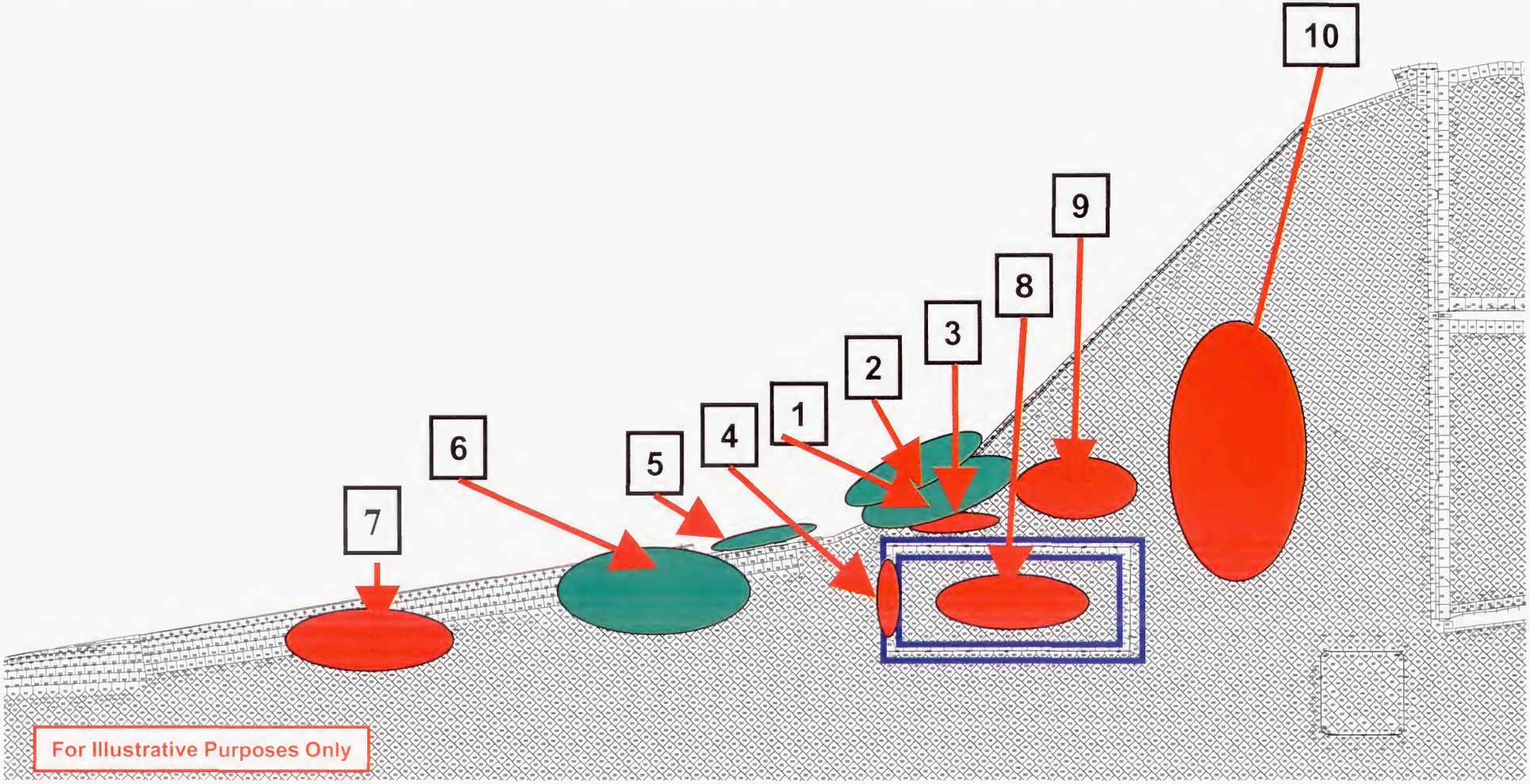
- Breach suspected in Left Wing.
- Begin with Factual Observations (Fact Sheets)
- Let Factual Observations guide the initial analysis.
- Initial Failure analysis included Left Wing:
  - Midbody Panel
  - Main Landing Gear Strut
  - Uplock Rollers
  - Tires
  - Leading Edge Carrier Panel Fastners
  - Tiles
  - Leading edge RCC material deposit
- M&P Failure Analysis Leads were assigned for each

Highest Level Questions

- Where (location in vehicle) did breach(es) occur?
- What specific component(s) failed and how?
- What was the sequence of events?

Initial Failure Scenarios and Breach Locations – April 14th, 2003

Scenarios Team

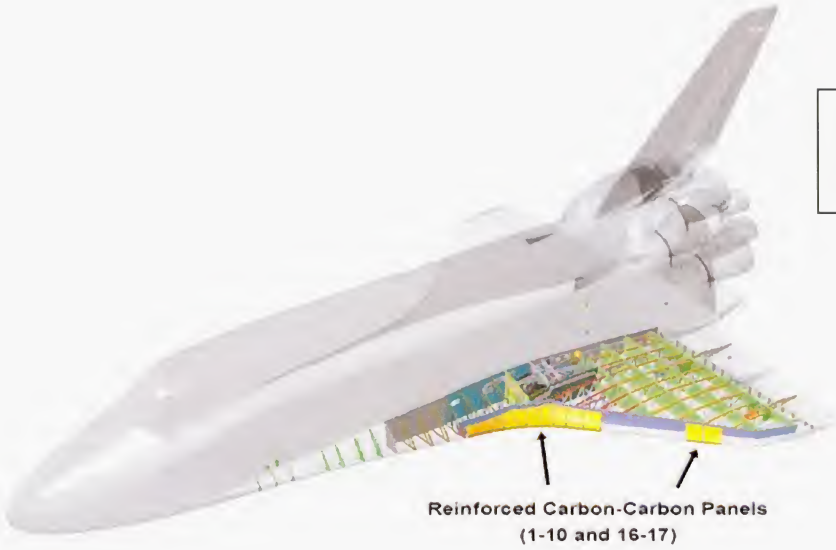


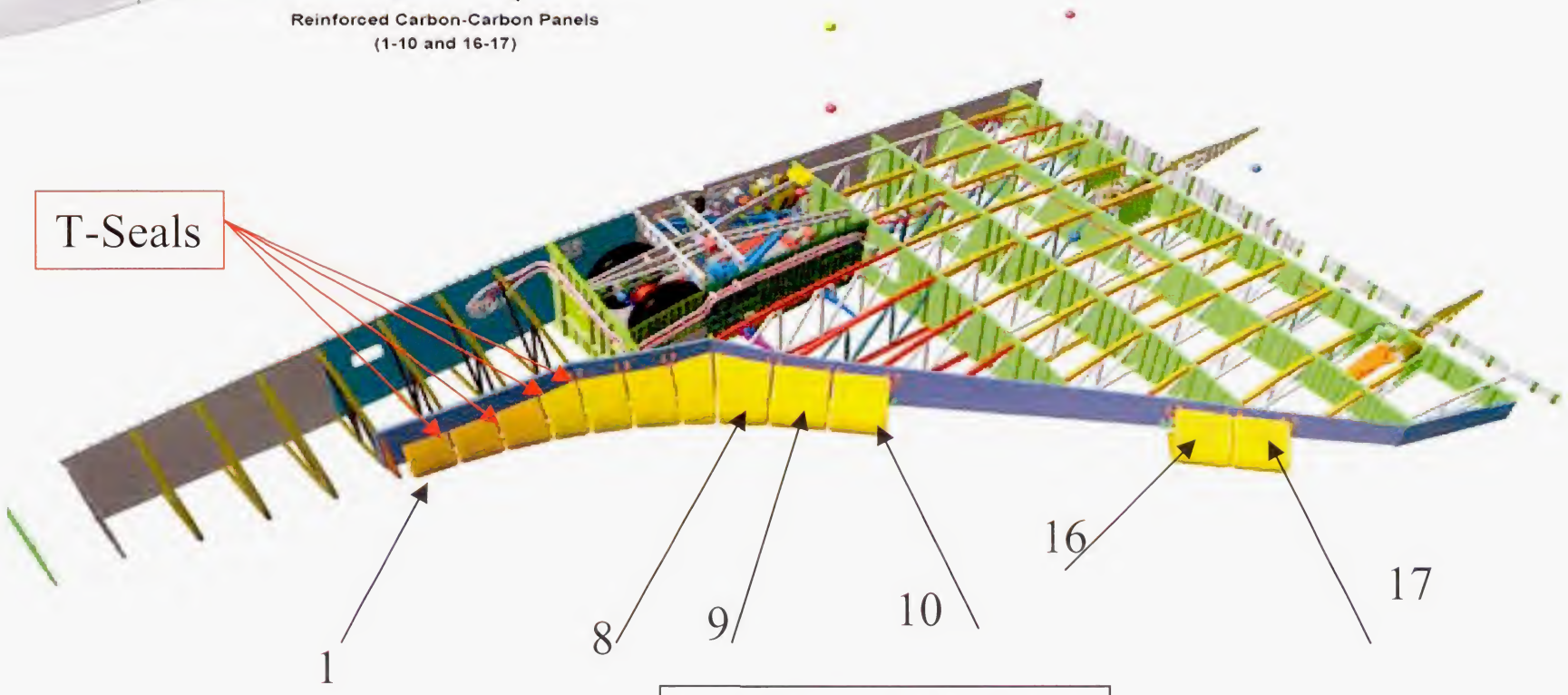
Key Finding

- MADS/OEX Data Recorder Found–"black box".
- Key thermocouple inside and outside left wing leading edge panel 9.
- Temperature in this location starts increasing prior to early debri observations.

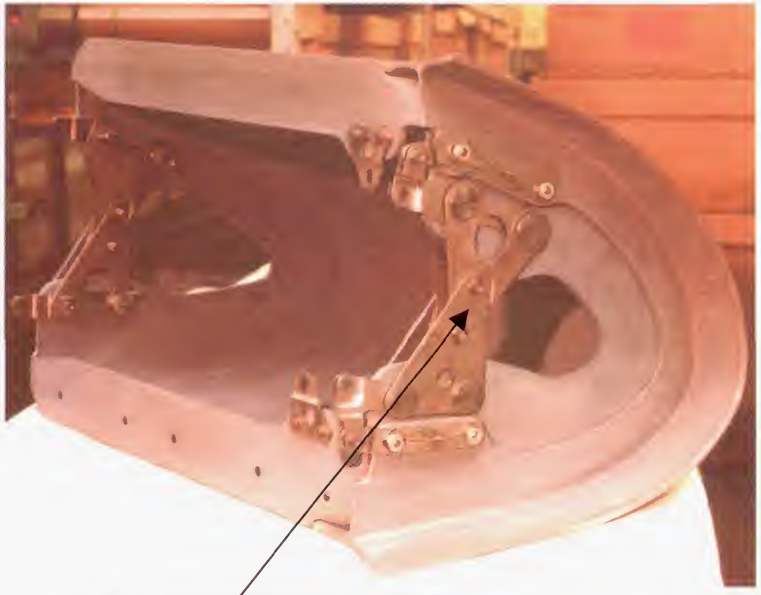
Spotlight/focus shifts to Left wing leading edge damage

Left Wing Leading Edge





RCC Panel Numbers

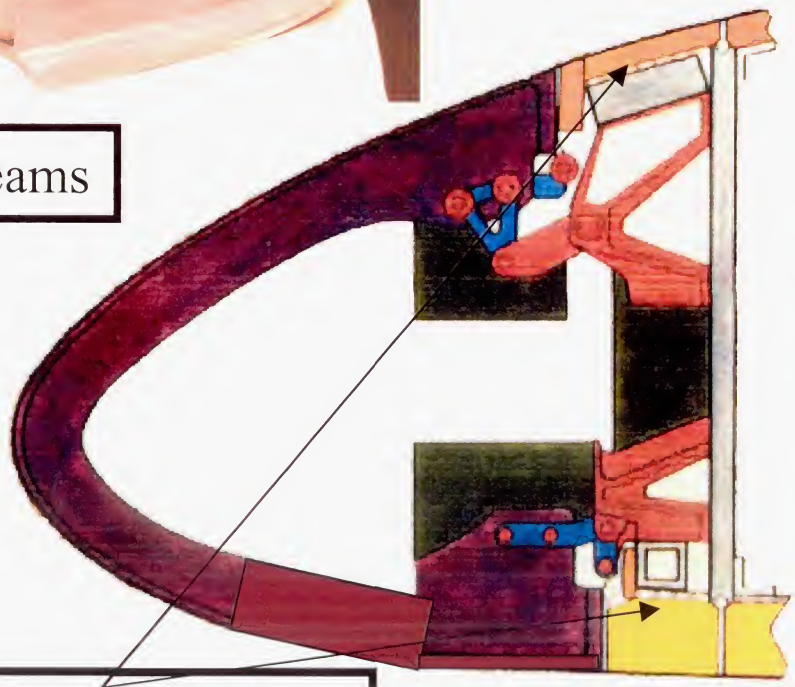


Spanner Beams

Dynaflex insulation – In601 foil with cerachrome fibers inside

RCC panel

RCC rib



Closeout/Carrier Panels and Tiles

RCC
Aluminum
LI2200
LI900
Inconel-Dynaflex
Inconel 718
A-286 steel

NASA

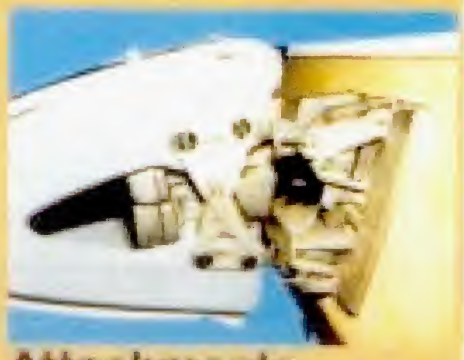
S-82-00703

Space Shuttle
Wing Leading Edge System

RCC Wing Panel

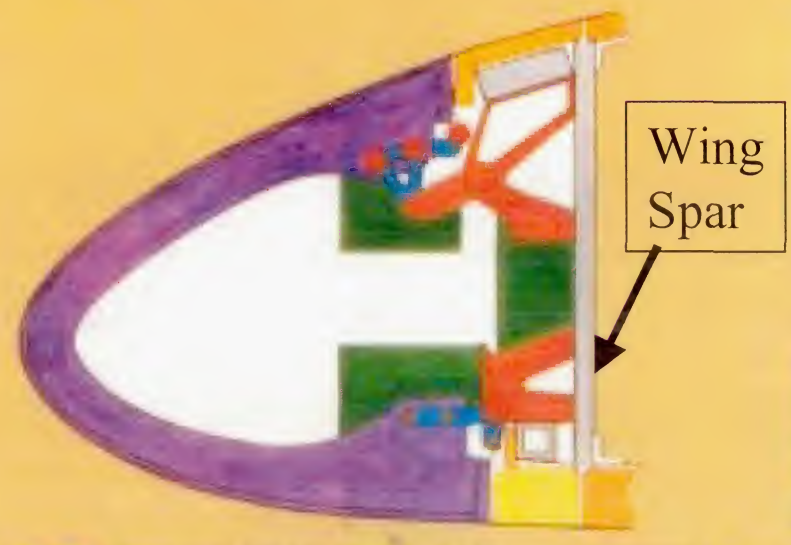
Upper Access Panel

Ear Muff Insulation



Attachments
Inconel 718 A-286

Spar Insulation



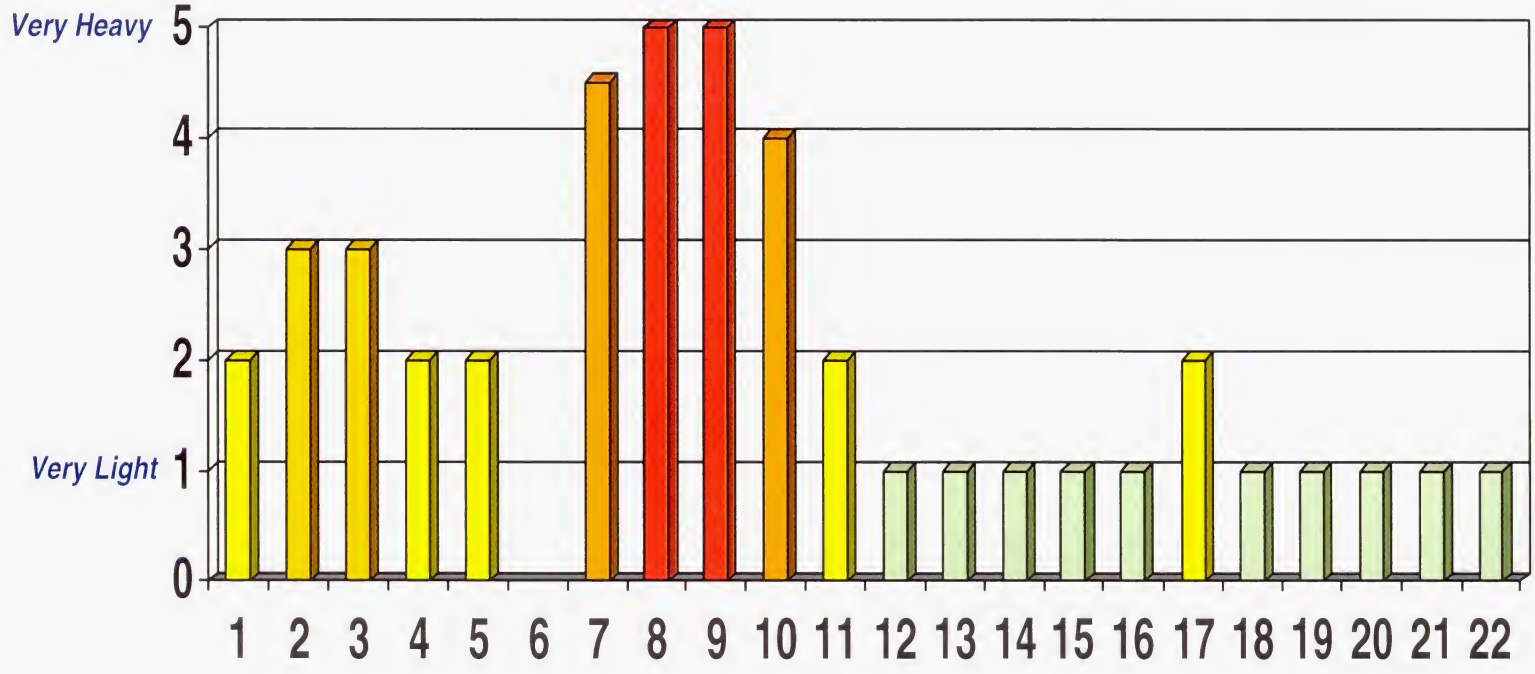
Lower Access Panel

LI2200 Inconel 718 RCC Inconel-
LI900 A-286 steel Aluminum Dynaflex

Left Wing Leading Edge Heat Damage Observations

- Heavy "Slag" deposits on select RCC panels.
- Eroded and knife-edged RCC rib sections.
- Excessive overheating and slumping of carrier panel tiles.
- Missing or molten attachment bolts but intact bushings.
- Deposit mainly on "inside" RCC panel.
- Deposit on some fractured RCC surface.

Qualitative Deposition Assessment: "Very Light" to "Very Heavy"



Distribution of "slag" deposition volume was centered around panels 8 & 9 on Left Wing Leading Edge RCC.

Example Debris, LH RCC 8

SLAG Deposit on "INSIDE" RCC

High Level Questions

Sample the slag deposits on RCC & Tiles to:

- Identify the location of breach in the wing leading edge.
- Identify the sequence of deposition/events
- Understand plasma flow direction and related thermal damage.

Analysis Plan Challenges

- Understand Pros and Cons of Analysis Techniques (destructive and non-destructive)
  - Objective is to downselect analysis techniques fast.
- What are the leading edge materials?
- Understand Chemistry of reactions with atmospheric elements.
- Understand effects of melting and mixing of different materials.
- All analysis to be complete by end of May, 2003. Wrap-up in June.

Analysis Techniques

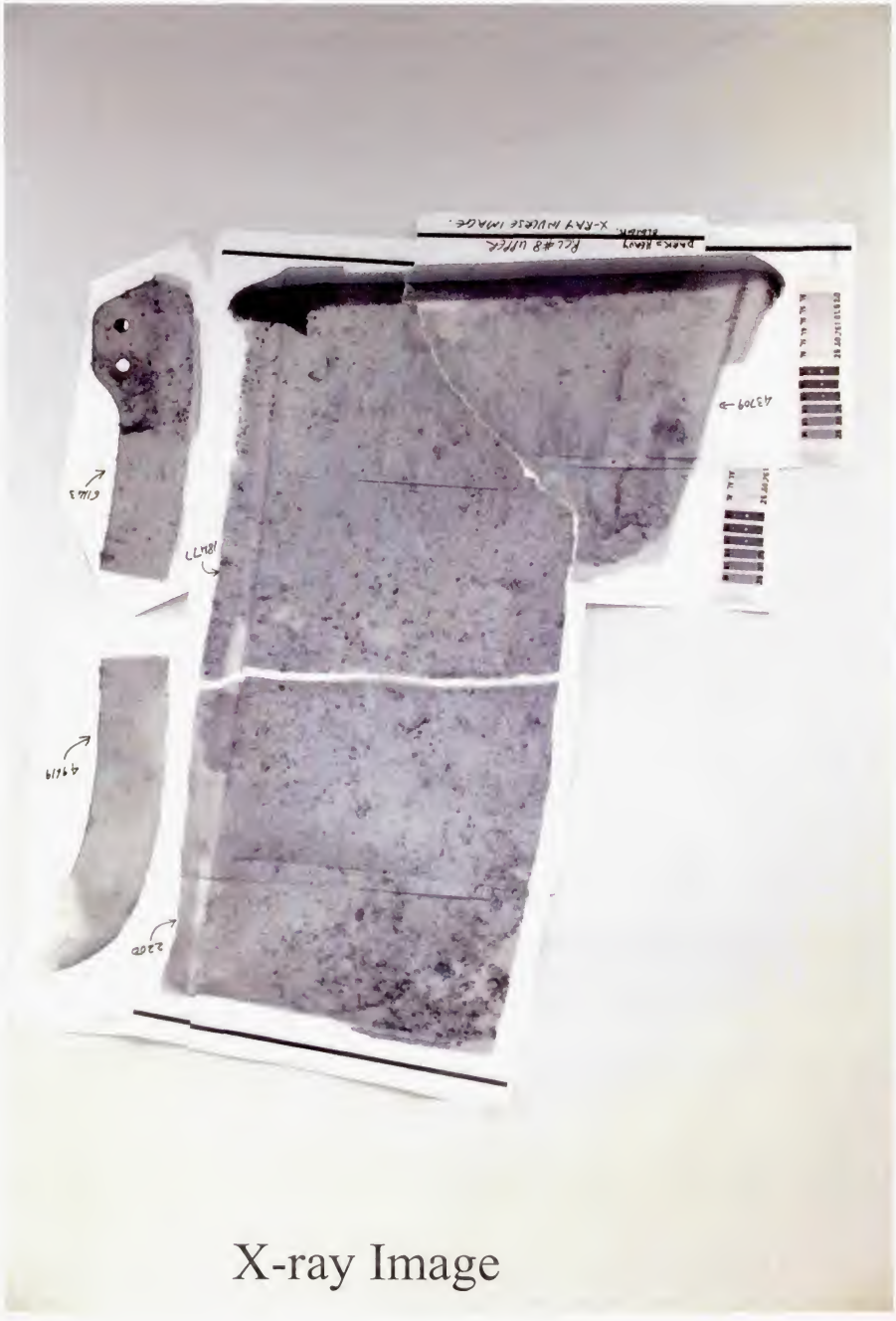
Analysis Technique	Purpose	Why/Advantages
Photography	Photo documentation	Documentation to maintain traceability
Scanning Electron Microscopy – SEM/EDS	Semi-quantitative elemental composition	Elements present, identify difference between top and bottom of sample
X-ray Diffraction - XRD	Identify compounds	Identify compounds of crystalline structure
Electron Microprobe	Identify elements	Determine exact composition
Fourier Transform Infra-Red - FTIR	Qualitative organic composition	If organic, aid in identification
ESCA/XPS	Identify inorganic & organic compounds	Aid in tracking of oxidation states, such al oxide; compound identification
Metallography + SEM	Layering of material	Composition through deposit layers
Inductively coupled plasma - ICAP	Quantitative elemental composition	Elements present, Quantify bulk composition of sample
NDE Inspections- Radiography, CT, Ultrasonics	Non-destructive Inspection and identification	See through the material, identify differences in materials, identify defects

Repeatability and Reproducibility of results emphasized

Approach and Downselection of Analysis Techniques

- Radiograph RCC panels & Tiles
- Strategically locate samples - minimize the sample count. Two samples of each feature.
- Use diagnostic techniques (X-section, SEM, Microprobe, XRD) to identify:
  - Content of slag
  - Layering of slag
- Use "Interpretation Criteria" to correlate deposit analysis <==> WLE source material

Apply results to ALL radiographs and visual features to answer the high level questions.

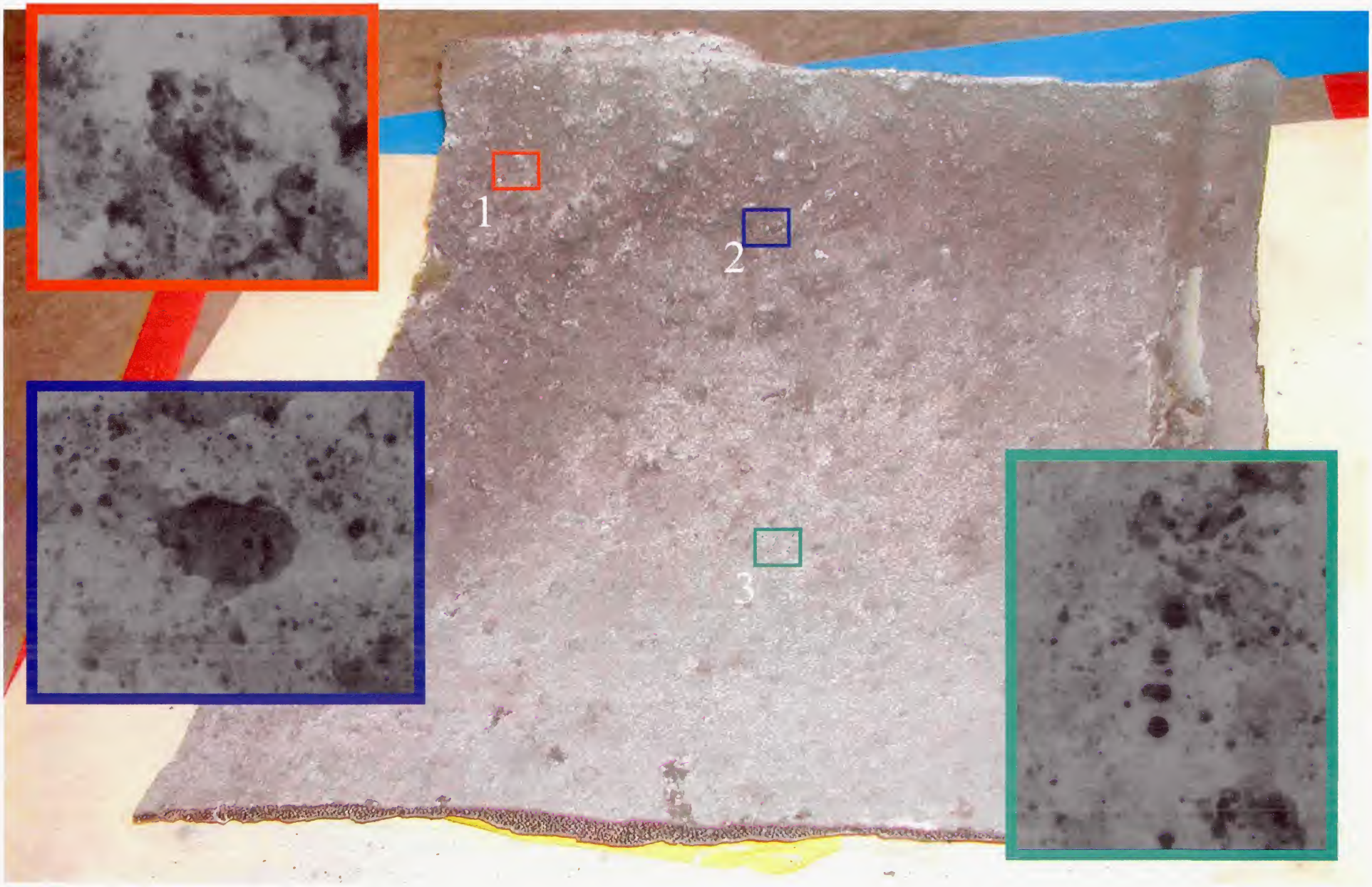


X-ray Image

Hardware

Left Wing RCC panel 8. Inside View.

2200, LH RCC #8 Upper Apex, Part I, Matches 18477



Interpretation Criteria - Examples

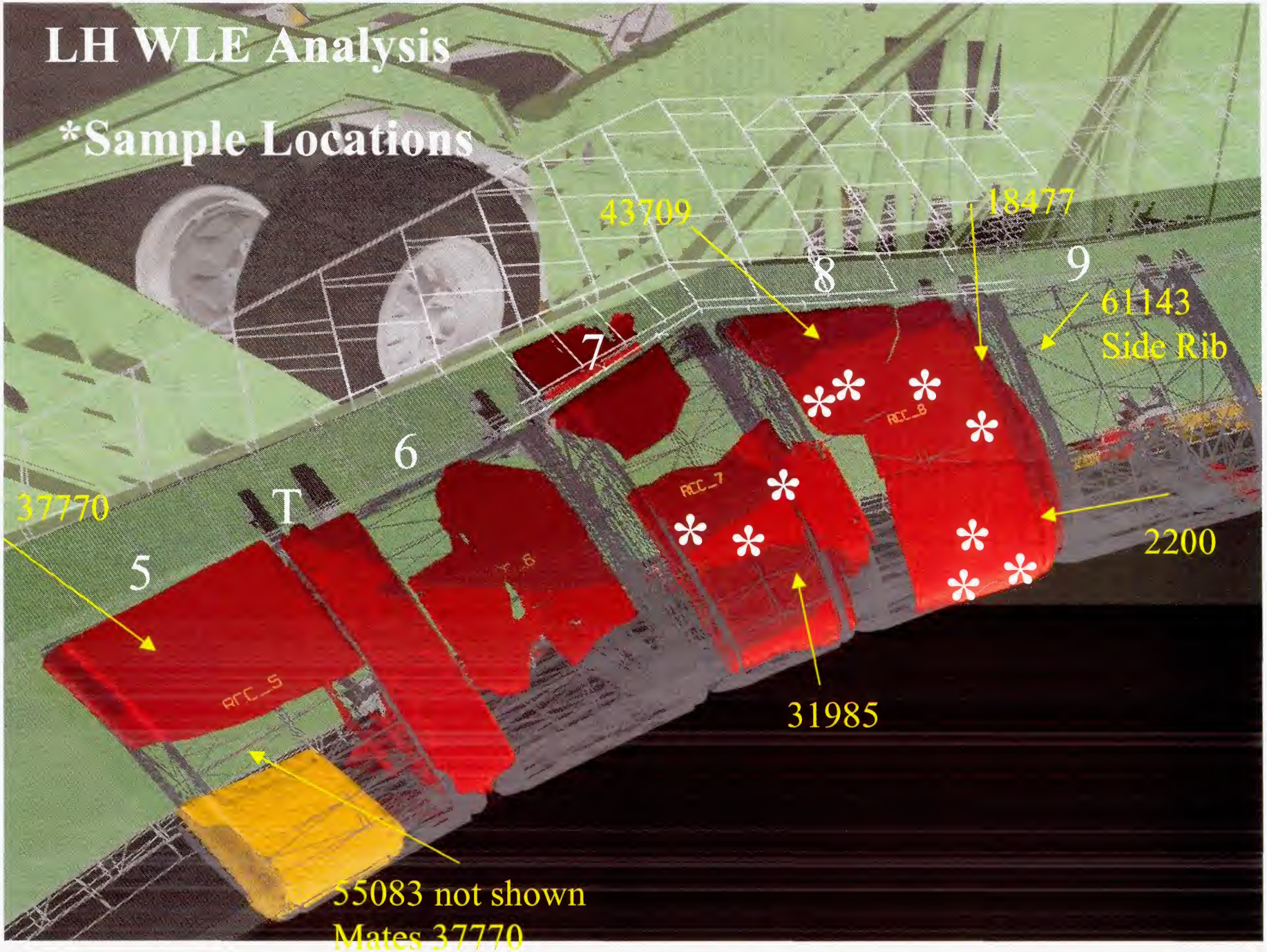
- **How to identify specific alloys in the deposit?**
  - A286 or IN601, IN718, IN625 can be distinguished based on (Ni/Fe) ratio and evidence and amounts of Mo, Nb, Co and Ti.
  - 2024 can be identified by presence of metallic Al + Cu, Al_2O_3 + Cu.
- **How to identify Cerachrome in deposit?**
  - Cerachrome is approximately 43%$Al_2O_3$53%$SiO_2$3%Cr_2O_3.
  - It can be identified from a combination of back-scattered imaging, color, x-ray diffraction and presence and quantification of Al, Si, O, & Cr.
- **How to identify SiO2 from Tile?**
  - SiO2 from tile will not have with other elements as in cerachrome. It could still pick up a coating of alumina then morphological features will be used to distinguish.

MSFC Contribution

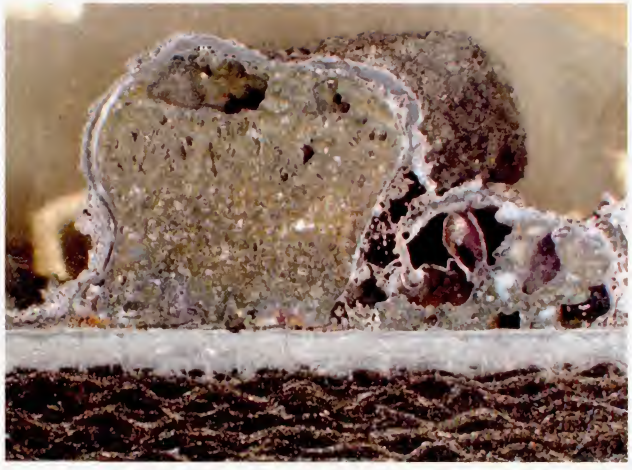
- Help Organize, Plan, and Co-ordinate all sampling activity.
- Metallography, Microprobe, & SEM.
- Generated 1000 pages of data & reports in 6 weeks.

Microprobe – Greg Jerman

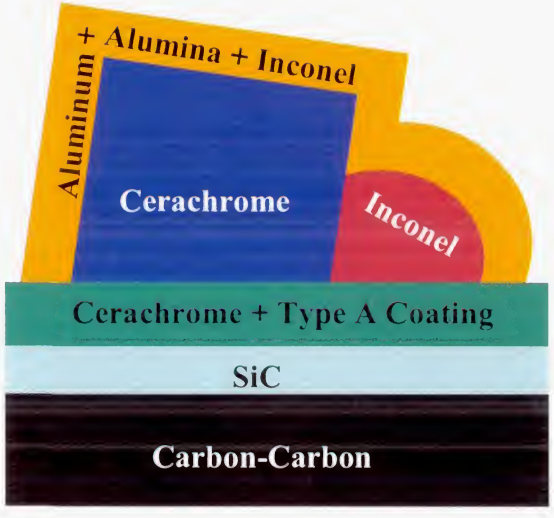
Field Emission SEM – James Coston

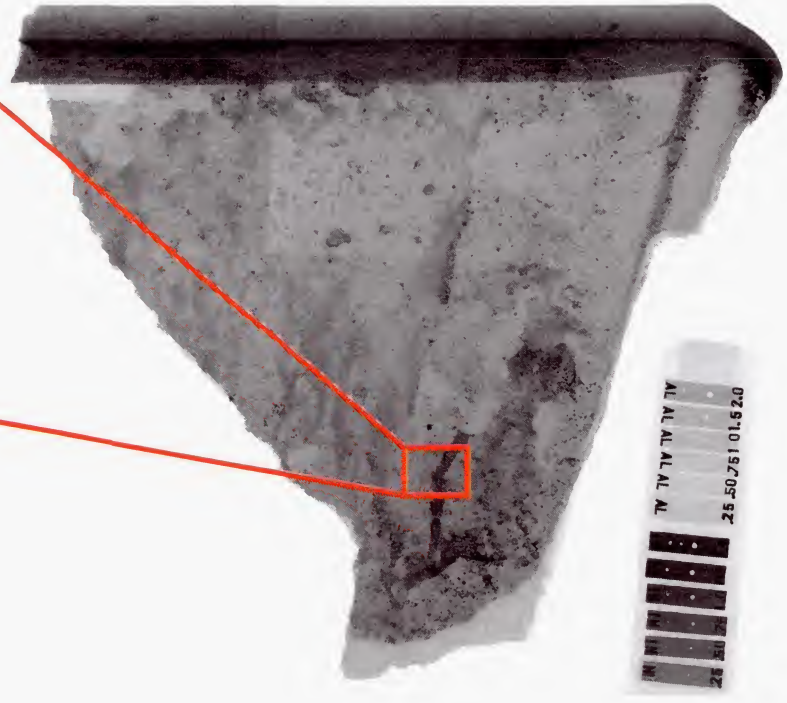

LH WLE Analysis
*Sample Locations
43709
18477
8
9
61143
Side Rib
7
6
37770
T
5
2200
31985
55083 not shown
Mates 37770

LH RCC #8 - Slag Feature 1
Thick Tear Shaped



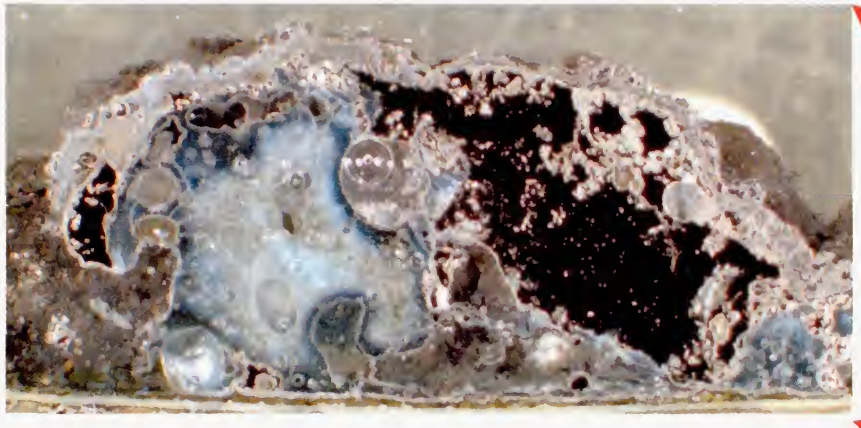
Slag Item 43709, Sample 2A1



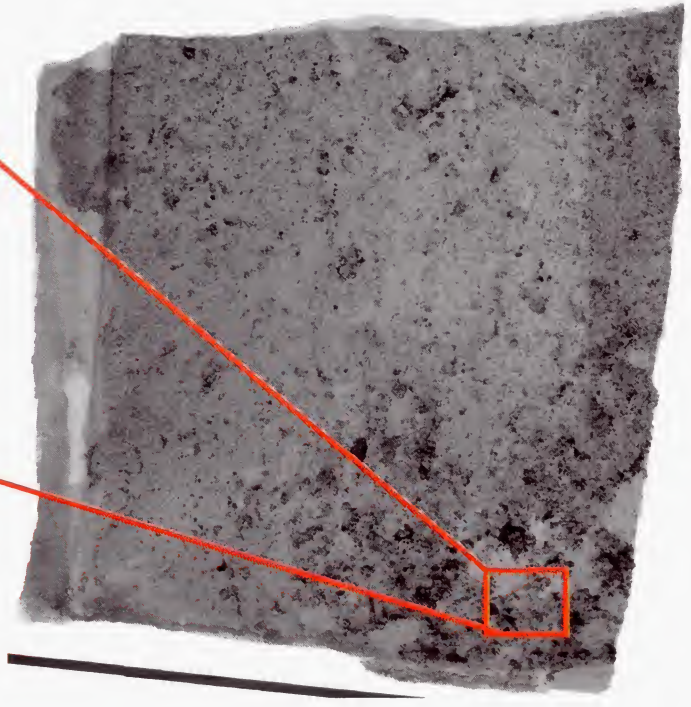


Radiograph of Item 43709

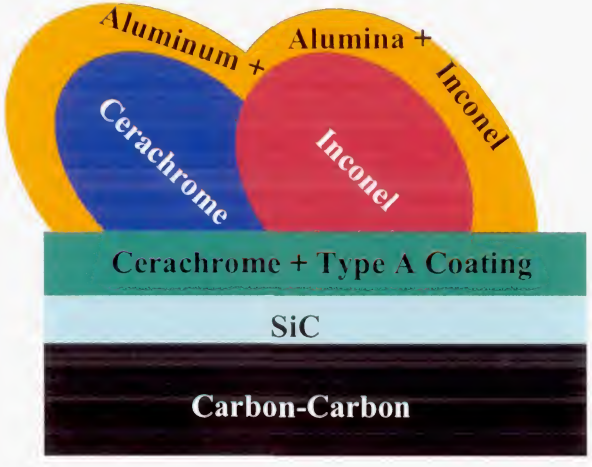
LH RCC #8 - Slag Feature 2
Thick Globules



Slag Item 2200, Sample 6A1

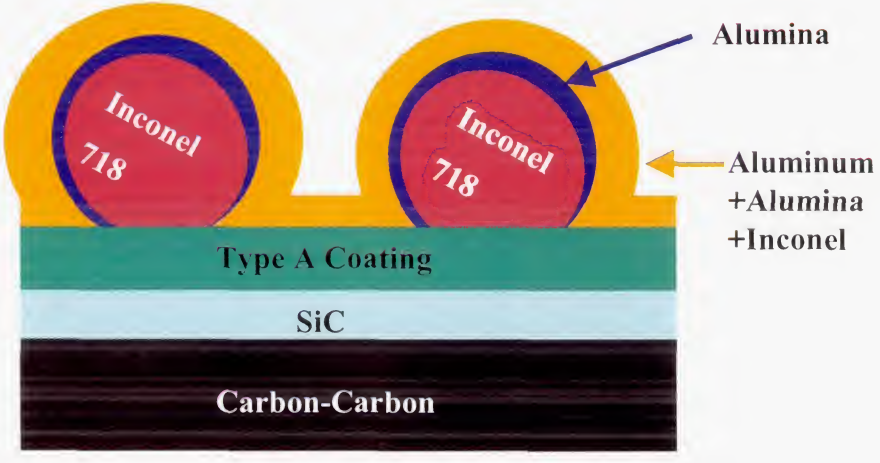


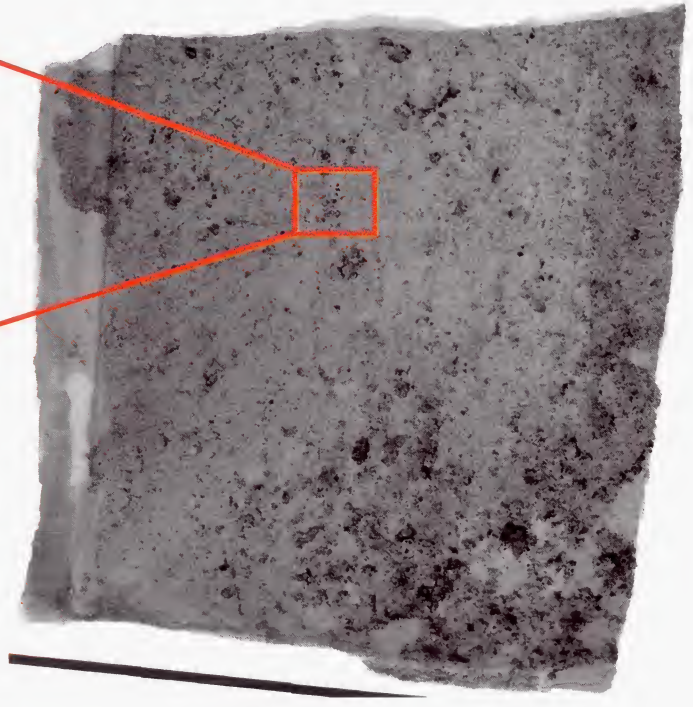
Radiograph of Item 2200



LH RCC #8 - Slag Feature 3 Spheroids

Slag Item 2200, Sample 6C1

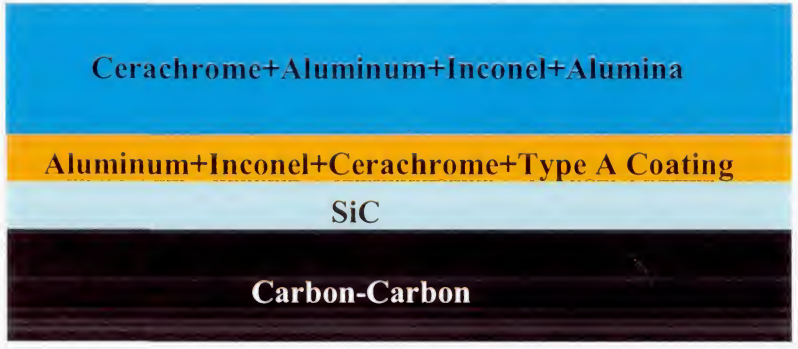


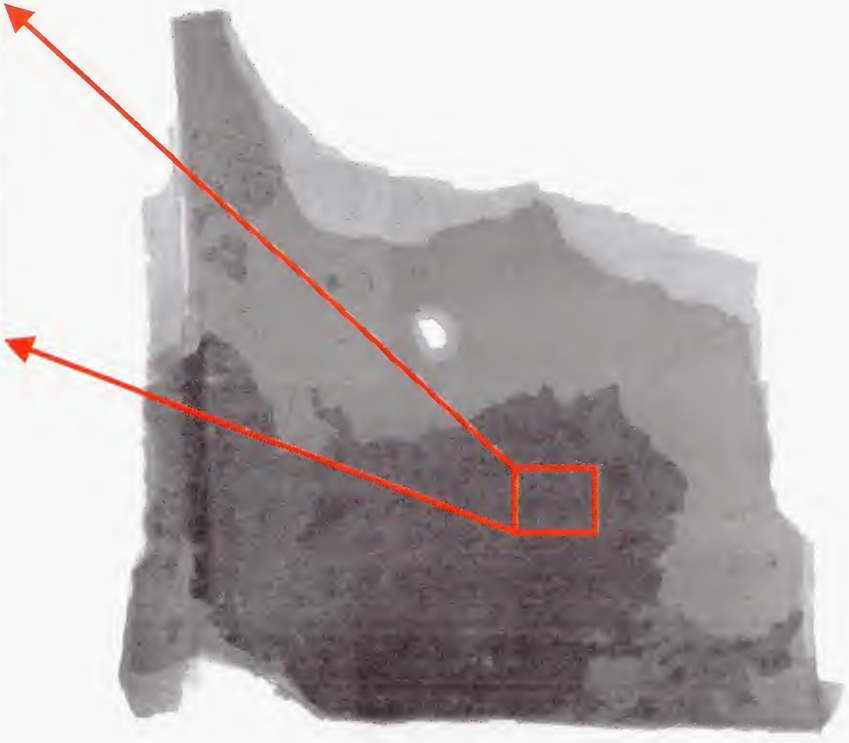


Radiograph of Slag Item 2200

RH RCC #8 - Slag Feature 4
Uniform Deposit

Slag Item 16523, Sample 4A1





Radiograph of Item 16523

RCC Slag Significant Findings
LH RCC #8

- Large amounts of melted ceramic cerachrome insulator
  - ➢ High temperature >3200°F
- No indication of stainless steel spar fittings (A286) in slag
  - ➢ Breach location away from spar fittings
- Cerachrome + Inconel in first deposited layers
  - ➢ Melting of spanner/foil/fittings + Insulator
- Aluminum deposition secondary event

Slag layering suggests plasma impingement location

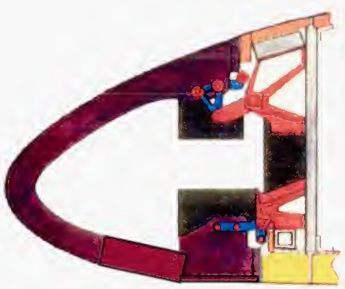
Slag distribution & shape suggests plasma flow direction and deposition duration

RCC Slag Significant Findings
-All RCC other than LH RCC #8
- Including RH RCC panels

- All analyzed slag layers contain aluminum
  - ➢ CONCURRENT Spar/Inconel/Insulator melting

- Slag is generally uniform and relatively thin
  - ➢ No region where melting was concentrated i.e. plasma heating for short periods

Reconstructed View
LH CPanel 9 Tiles, lower



RCC
Aluminum
LI2200
LI900
Inconel-Dynaflex
Inconel 718
A-286 steel

Horse Collar Fabric Deposit

C
P
8

Insert

Tile Slumping

57754 # 22571 # 50338 # 16692

Molten Slag on Tile

Spar

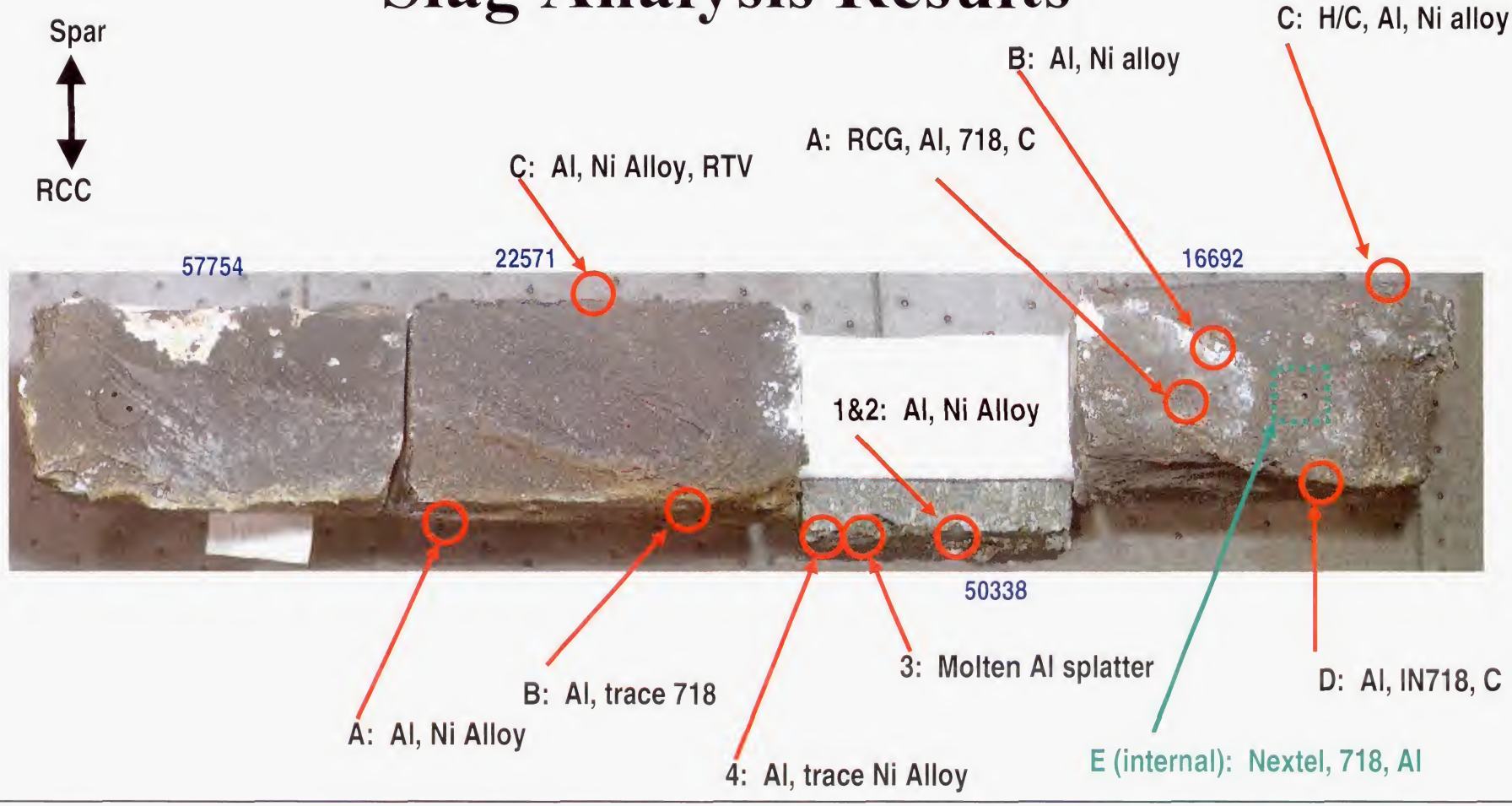
RCC

Realtime X-ray, Sidewall View

Carrier Panel

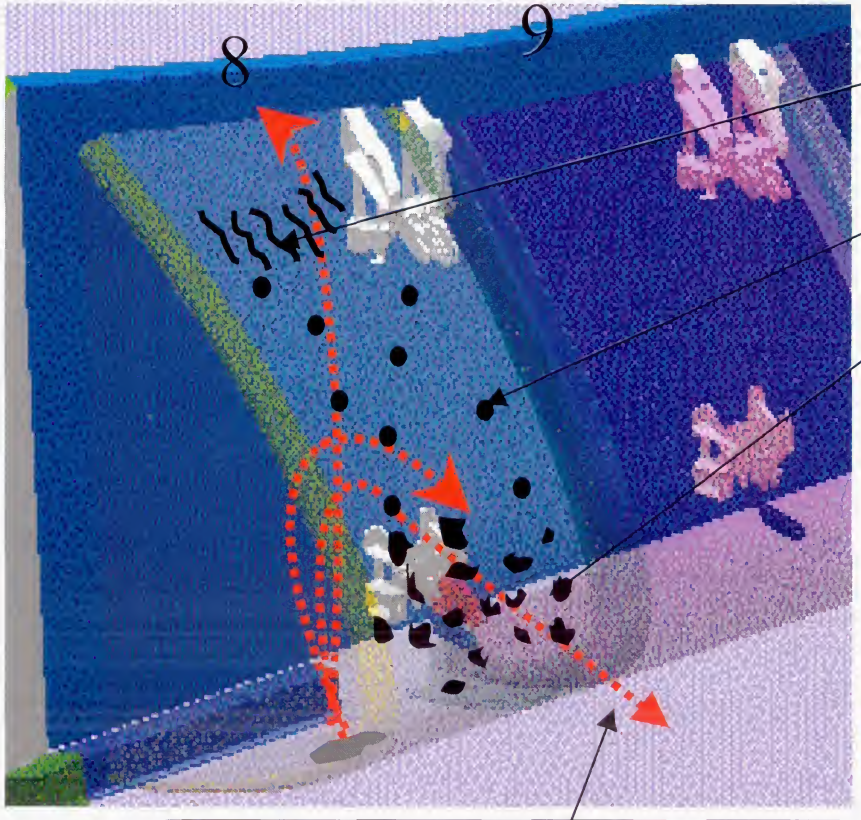
High-Z material

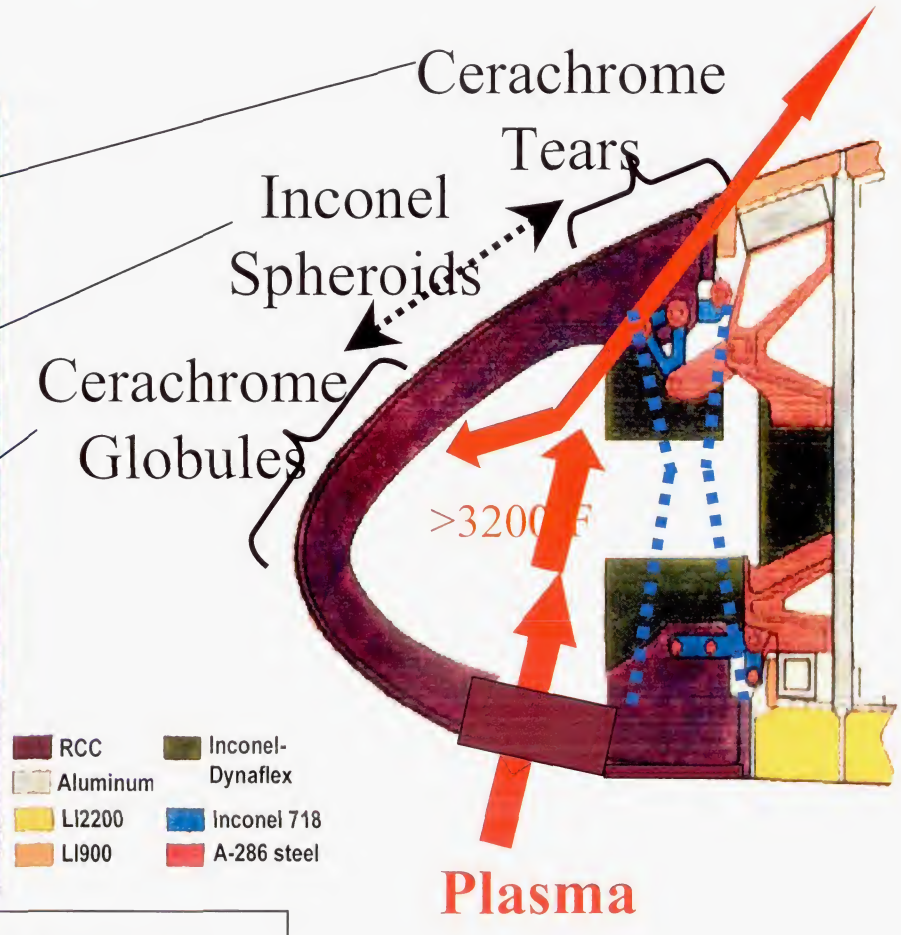
Reconstructed View
LH Carrier Panel 9 Tiles, Lower
Slag Analysis Results



These findings suggest flow of material from inside the RCC out through the upper and lower CP locations.

Proposed Breach Location & Plasma Flow Based On Slag Results





Flow Exiting through RCC 8 on to lower Carrier Panel 9 tiles